THE LHC INJECTORS UPGRADE (LIU) PROJECT AT CERN: ION INJECTOR CHAIN

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Abstract

The LHC injector chain for Pb-ion beams at CERN consists of Linac3, the accumulator ring LEIR, the PS and the SPS. In the context of the LHC injectors upgrade project an intense program of machine development studies has been performed in the last two years to maximise the intensity of Pb-ion beams at LHC injection. In this paper we present an analysis of the operational performance achieved so far, with the goal of 1) identifying the remaining performance bottlenecks along the chain and possible areas for improvement, and 2) to optimize the Pb-ion beam production scheme for the High Luminosity LHC era. A consistent set of beam parameters for the HL-LHC era has been established taking into account the already achieved improvements as well as foreseen upgrades still to be implemented, such as slip stacking in the SPS.

INTRODUCTION

The LHC injector chain for Pb-ion beams at CERN consists of Linac3, the accumulator ring LEIR, the PS and the SPS [1]. The LHC injectors upgrade project (LIU) [2] aims at upgrading the existing accelerator chain in view of the increased beam performance required for the High Luminosity LHC (HL-LHC) era, which starts for the heavy ion program in 2021 after the upgrade of the ALICE detector in Long Shutdown 2 (LS2). In simplified terms, the HL-LHC is requested to deliver an integrated luminosity of 10 nb^{-1} of Pb-Pb collisions at top energy to each of the ALICE, ATLAS and CMS experiments. Achieving this goal in four heavy-ion runs requires about a factor 2 higher total intensity from the injectors as compared to the best performance reached so far. It should be emphasized that the luminosity evolution for Pb-Pb collisions in the LHC is strongly “burn-off” dominated and therefore the total number of ions in the LHC is the main figure of merit for the performance of the injectors.

Experimental studies have been performed in 2015 and 2016 in order to maximize the intensity from the ion injector chain in the frame of the LIU project. In the following, the Pb-ion beam intensities achieved in 2015 and 2016 are compared. The remaining performance bottlenecks are discussed. Based on these results, the LIU beam production scheme and a new set of target parameters are established.

PERFORMANCE ACHIEVED IN 2015/16

A detailed analysis of the beam parameters along the injector chain during the 2016 proton-Pb run including a description of the beam production scheme is given in Ref. [3]. Figure 1 shows a comparison of the intensity along the injector chain. Although not explicitly shown in the graph, the beam intensity from Linac3 could be increased by almost 40% compared to 2015 [3]. This was the result of a modification of the source extraction system carried out as part of the LIU project to remove an aperture restriction [4]. Consequently, about 30% more Pb^{54+} ions per cycle could be accumulated in LEIR in 2016 using the same injection plateau that accommodates 7 pulses from Linac3 spaced by 200 ms [5]. The critical part of the LEIR cycle is the RF capture of the e-cooled coasting beam and the early part of acceleration. Excessive losses during this phase limited the total intensity of the two bunches at LEIR extraction to about 12×10^8 Pb-ions in the past [6]. This limitation seems to be caused by non-linear betatron resonances in combination with the large incoherent space charge tune spread when the beam is bunched [7]. As a result of extensive studies in 2016 these losses could be controlled by optimizing the machine settings including a modified RF capture [5]. Record intensities of up to 18.4×10^8 Pb-ions at LEIR extraction were achieved during machine studies, while the operationally achieved values were only slightly lower. The transfer from LEIR to the PS could also be improved in 2016 by optimizing the steering in the transfer line such that injection into the PS was virtually loss-free. In the PS itself the bunch splitting at intermediate energy, as foreseen in the original production scheme, was re-introduced on the operational beam in 2016 with the aim of mitigating losses in the SPS.

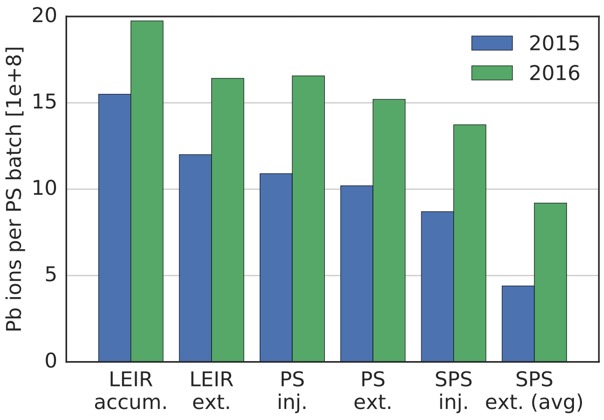

Figure 1: Comparison of operationally achieved intensities through the LHC injector chain in 2015 and 2016.

In this configuration no particular issues with the higher beam intensity were encountered in the PS. In fact the beam lifetime in the PS is rather dominated by interaction of the partially stripped Pb^{54+} with residual gas molecules. In the transfer line from the PS to the SPS the ions are fully stripped to Pb^{82+}, which explains the observed few percent reduction in intensity. The largest relative loss of intensity along the entire accelerator chain is observed in the SPS. With the bunch splitting in the PS introduced in 2016 the intensity per bunch at SPS injection was similar as in 2015 despite the almost twice higher total intensity. A slight improvement of the transmission in the SPS was achieved in 2016, partially due to the fact that a shorter cycle was used compared to 2015 as explained below. In both cases the "Q20" optics was used [8].

The SPS cycle has a long plateau in order to accumulate several injections from the PS with a spacing of 3.6 s. Therefore some of the bunches need to stay at SPS injection energy for tens of seconds. During this phase the beam suffers from transverse emittance growth of up to 80% and incoherent losses, most likely caused by a combination of Intra Beam Scattering effects and strong direct space charge with a maximum incoherent tune shift of about $\Delta Q_y = -0.3$. Losses are also encountered at the beginning of the ramp (mostly due to particles lost out of the RF bucket) and during transition crossing. Figure 2 shows a comparison of the intensity evolution along the operational Pb-ion cycles in 2015 and 2016. With the improved performance of the upstream machines, the average intensity per PS batch at SPS extraction could be almost doubled. Hence a higher total intensity could be achieved with 7 injections in 2016 as compared to 12 injections in 2015. However, it should be emphasized that this was only possible thanks to the bunch splitting introduced in the PS, since the transmission in the SPS is observed to degrade linearly with the intensity per bunch at injection as shown in Fig. 3. With the bunch splitting in the PS, similar values of intensity per bunch could be maintained in 2016 despite the significantly increased total intensity per injection. A slight improvement of the total transmission in the SPS was achieved by optimized machine settings (e.g. chromaticity) and, in particular, by the shorter injection plateau as the beam suffered less from the losses described above. For LIU the number of injections will have to be increased again in order to optimize the total number of ions in the LHC and thus the integrated luminosity. The SPS therefore clearly remains the bottleneck of the Pb-ion injector chain and no clear mitigation path to further reduce losses has been identified so far.

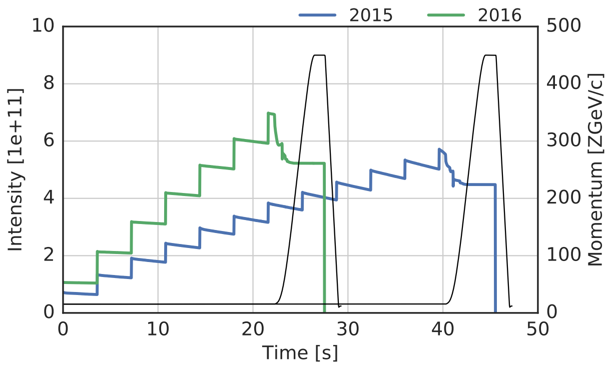

Figure 2: Typical intensity evolution along the operational Pb-ion cycles in 2016 in comparison to 2015.

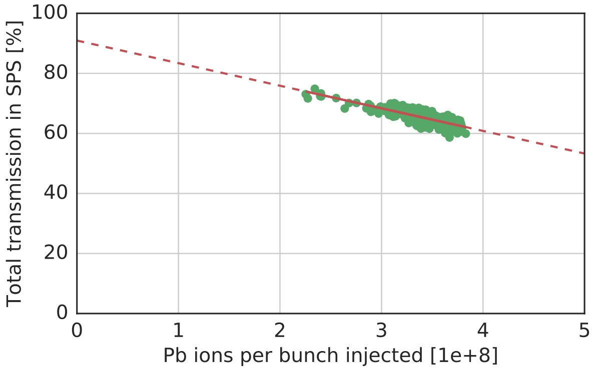

Figure 3: Total transmission in the SPS as function of intensity per bunch at injection for the operationally delivered beams in 2016 (7 injections from the PS).

LIU BEAM PARAMETERS

The first line in Table 1 provides a summary of the beam parameter request established by the HL-LHC project in 2015 [9]. As described in the previous section, the losses in the SPS effectively impose a limit on the achievable intensity per bunch. To reach the total number of ions at LHC injection required for the HL-LHC luminosity goals, the future scenarios are therefore based on a 50 ns bunch spacing in contrast to the presently used 100 ns. This reduced bunch spacing cannot be achieved by RF manipulations in the PS using the existing RF systems (as routinely performed for proton beams), since the PS extraction energy is too close to the transition energy. Instead, the 50 ns bunch spacing will be achieved by momentum slip stacking at an intermediate energy plateau in the SPS, which will become possible with the upgrade of the SPS LLRF system in LS2 as part of the LIU project. The feasibility of the momentum slip stacking scheme in the SPS was checked by macroparticle simulations without intensity effects [2]: Two bunch trains can be captured independently by two pairs of the 200 MHz travelling wave cavities and brought to slightly different energies so that they are slipping towards each other in azimuth. When the two trains are interleaved, the reverse procedure takes place in order to approach the two batches in energy with RF programs designed accordingly. Once the two bunch trains are close enough in energy and in the correct azimuthal position, they are recaptured at average frequency and filament into a larger bucket. As seen in the simulations, optimization of this process is crucial in order to keep losses after recapture below 5%. It is also expected that the longitudinal

Table 1: Selection of Relevant Parameters at LHC Injection as Requested by HL-LHC and/or Targeted by LIU

Parameter target (est.)	ions/LHC ring	ions/bunch	norm. emittance	bunches/LHC ring	MKI gap	abort gap
HL-LHC (2015)	2.6e+11	2.1e+8	1.3 μm	1245	900 ns	3300 ns
LIU TDR (2016)	2.0e+11	1.7e+8	1.3 μm	1152	900 ns	3300 ns
LIU/HL-LHC (2017)	**2.4e+11**	**1.9e+8**	**1.5 μm**	**1256**	**800 ns**	**2900 ns**

emittance will increase by a factor 2.5 and therefore bunch rotation at SPS extraction will become necessary for injecting the beam into the 400 MHz buckets of the LHC. The second line in Table 1 presents the expected beam parameter reach with slip stacking in the SPS and the improvements in the pre-injectors as described in the LIU Technical Design Report (TDR) Volume 2 [2] from 2016, which corresponds to about 80% of the total intensity requested by HL-LHC.

Based on the excellent performance achieved in 2016 an updated projection of the performance reach in the LIU era is made in the following. Due to the losses on the SPS injection plateau described in the previous section, the highest total number of ions in the LHC is not necessarily obtained for the largest number of injections into the SPS despite the relatively long LHC injection kicker gap. The beam intensity degradation due to the waiting time in the SPS t_S and in the LHC t_L can be approximated by a function of the form [10]

$$N(t_S,t_L) = N_o\cdot\left[1 - a_S\cdot\left(1 - e^{-\frac{t_S}{\tau_S}}\right)\right]\cdot\left[1 - a_L\cdot\left(1 - e^{-\frac{t_L}{\tau_L}}\right)\right] \quad (1)$$

where parameters with a subscript S describe losses in the SPS and parameters with subscript L the losses on the LHC injection plateau. The following parameters are obtained from a global fit of the bunch-by-bunch intensities at LHC injection of the Pb-ion fills in 2016: $N_0 = 2.37\times10^8$, $a_S = 0.3$, $\tau_S = 45$ s, $a_L = 231$ and $\tau_L = 9e+6$ s. From these numbers it is clear that the losses on the LHC injection plateau are almost negligible compared to the losses in the SPS. This is also illustrated in Fig. 4, which shows a typical fill in 2016 together with the corresponding result of the model. This model is used to project the total number of ions in the LHC as a function of the number of PS-to-SPS injections for realistic filling scenarios in the LIU era as shown in Fig. 5 (including 5% losses due to slip stacking). For comparison the case without slip stacking is also shown. The calculation assumes a slightly reduced LHC injection kicker (MKI) rise-time of 800 ns compared to the usual 900 ns, as successfully tested with beam in LHC machine studies in 2016 [11]. Also the LHC abort gap is assumed to be slightly reduced from 3300 ns to 2900 ns. The total number of ions in the LHC approaches an asymptotic limit for about 14 or more PS-to-SPS injections. As indicated in the graph, this asymptotic limit is slightly above the total intensity required to reach the HL-LHC luminosity goals based on a revised luminosity projection from 2016 [12]. The scenario with 14 SPS injections is the updated and common LIU/HL-LHC beam parameter target as summarized in the last line of Table 1.

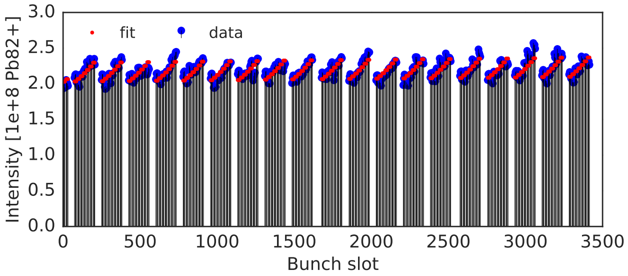

Figure 4: Bunch-by-bunch intensity in the LHC after the last injection for a typical fill in 2016 (blue) and the fitted intensity model (red). Larger bunch slots are filled last.

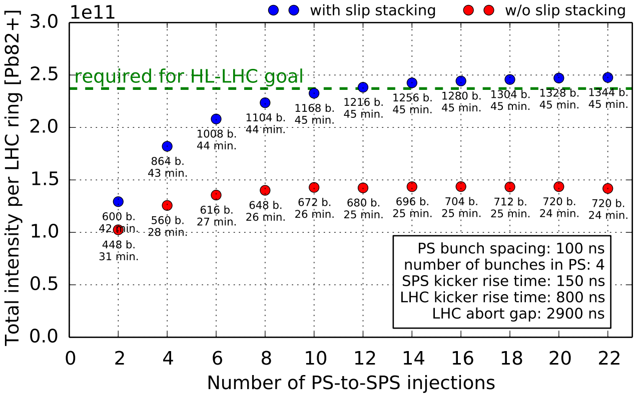

Figure 5: Projected total number of ions in the LHC as a function of the number of PS-to-SPS transfers with (blue) and without (red) slip stacking assuming the model parameters described in the text. Minimum LHC filling time and number of bunches per LHC ring are also indicated.

SUMMARY AND CONCLUSIONS

The already implemented LIU upgrades (such as the modifications of the Linac3 source extraction system) in combination with an intense machine study program resulted in a significantly improved performance of the LHC ion injector chain in 2016. The SPS clearly remains the bottleneck, calling for further studies to better understand the mechanisms limiting the intensity per bunch. Nevertheless, the implementation of the momentum slip stacking in the SPS, which will become possible with the foreseen upgrade of the LLRF system as part of LIU, will allow reaching the total ion intensity requested by the HL-LHC project as defined by updated common LIU/HL-LHC target beam parameters.

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